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Developing an experimental database of burning characteristics of combustible informal dwelling materials based on South African informal settlement investigation

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Abstract

Informal settlements, which have little or no legal status and no official planning remit, such as slums, shacks and favelas, are exposed to an extensive risk of fire. Due to flammable construction materials of the dwellings, the combustibility and flammability of the materials of dwelling furnishings and the proximity and density of these settlements, fires can readily develop and spread to neighbouring dwellings. To understand the hazards related to fire development and spread, a database of material properties is required, however, the materials found within the informal settlement homes vary and are sometimes hard to define. Therefore, an accurate assessment of the common materials found in informal settlements, and their comparison to literature data, is required. This paper presents a total of 345 cone calorimeter tests used to develop a database of combustible materials found in informal settlements of the Western Cape in South Africa. Thirty-two different typical materials were collected from one South African informal settlement and heated by an electronic cone calorimeter. The critical heat flux for ignition was determined by decreasing the incident heat flux until no ignition occurrence. The materials were also heated under different heat fluxes of 30 kW/m^2, 50 kW/m^2 and 75 kW/m^2 to simulate their burning behaviour under different fire conditions. Other important parameters were obtained including ignition time, burning time, maximum heat release rate and flame height. Different materials contribute to fire development/spread/severity in different ways and phases: for the fire development inside the shack, PU foam, carpets and clothing are most important; for fire

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spread between dwelling: clothing, shade netting and tyre play a key role; meanwhile for fire severity, tyre, PU foam, carpets and Masonite timber need most notice. The experimental results can provide basic data for theoretical and numerical analysis of compartment fire development and spread in informal settlements.
Keywords: informal settlement; cone calorimeter; critical heat flux; burning rate; fire risk

1. Introduction

Urbanisation poses a massive sustainability challenge in terms of housing, infrastructure and basic services, amongst others [1]. It is estimated that 55% of the world's population now live in urban areas [2], and that around 30% of the urban population live in informal settlements in developing regions [3]. In addition, over one billion people across the globe currently live in informal settlements, and this number is increasing as 90% of urban growth is occurring in the Global South, adding 70 million new urban dwellers each year [1, 2], and is expected to reach 1.2 billion dwellers in Africa alone by 2050 a large proportion of which will live in informal settlements [4].

Fires are estimated to cause at least 150,000 deaths a year, which represents approximately 4.5% of all unintentional injury-related deaths worldwide in 2016. In comparison, the equivalent figure for war was 2%. Fire is also the fourth largest cause of accidental injury globally [3] with over 10 million disability-adjusted life years (DALY: one lost year of healthy life, either due to premature death or disability) were lost due to burn-related injuries in 2016 alone. There is a general lack of reliable, accurate and consistent data with respect to fire impact, death and injury statistics, with the WHO estimating a ±32.6% uncertainty in their data. However, it is estimated that over 95% of deaths and injuries due to fire are in low- and middle-income countries (LMICs), where death rates are nearly six times higher than in high-income countries

In the Global South, especially in informal settlement area, there are numerous examples of large scale fire illustrating the problem in 2018 alone [5]: Cebu, Philippines, January 2018 (326 dwelling destroyed, 3570 homeless); Kijiji, Kenya, January 2018 (6000 homeless); Dhaka, Bangladesh, March 2018 (1000 dwelling destroyed, 4484 homeless); Delhi, India, April 2018 (500 dwelling destroyed, 1000 homeless); Lambayog, Philippines, July 2018 (5000 dwelling destroyed); Khayelitsha of Cape Town, South Africa, October 2018 (1000 dwelling destroyed, 4000 homeless); Manaus, Brazil, December 2018 (600 dwelling destroyed, 2000 homeless).

These large informal settlement fires damage lives, livelihoods, and property causing major disruption to urban systems, and can be considered a 'shock' in resilience terms. However, fires in informal settlements are simultaneously a 'stress' on urban systems, as evidenced by the 5,448 reported informal dwelling fires in South Africa in 2015 (almost 15 per day). In Cape Town alone, which is called the 'fire capital of South Africa', annually there are approximately 500 deaths and 15,000 fire related hospital admissions due to fire, of which a substantial proportion are people from informal settlements [6]. Urban fires therefore exemplifies an 'extensive risk', i.e. the widespread risk "to repeated or persistent hazard conditions of low or moderate intensity, often of a highly localized nature, which can lead to debilitating cumulative disaster impacts" [6].

Urban fires are a man-made hazard that is symptomatic of informal urbanisation. These fires start, develop and spread due to a variety of factors, including: use of open flames for cooking and lighting; unsafe electrical use; combustible construction and furnishing materials; proximity and density of adjacent homes; narrow access ways for fire service interventions; and lack of adequate water supply. To mitigate the consequence of fire, understanding how fires develop and spread between dwellings is paramount.

Fires spread in informal settlements through three main processes: radiation, direct flame impingement, and fire-branding. Initial modelling analyses by the authors [7] has started to investigate the critical separation distance for radiation-based fire spread based on assumed properties of polymer foams. While it is anecdotally known that foam is used in informal dwellings (mainly for mattresses), other materials will also be potential fire spread mediums. However, very little is known about the specific types of materials the residents use for and in their homes, and in particular, their burning characteristics (Max Heat Release Rate, Critical Heat Flux, flame heights etc…), which are very important to understand fire development within informal settlement dwellings and fire spread between such dwellings.

However, no comprehensive research database exists for the large range of materials present in informal settlement. Most of the previous work has focused on the specific single components of household appliances and accessories, such as polymethyl methacrylate (PMMA), polystyrene and polymers [8-13]. Meanwhile, although the complicated materials in real situation were tested, the experimental conditions can vary considerably between studies making the results difficult to compare. For example, experiments including wood were conducted in cone calorimeter [11, 14]; curtains and draperies were burnt in different sizes of rooms [15, 16]; the studies about the mattresses were conducted in a furniture calorimeter or specific hood [17, 18]. All these different conditions render it difficult to compare and assess the fire risks of these combustible materials, in particular, when the ignition of solids are heavily dependent on the environmental and experimental conditions of the studies [19].

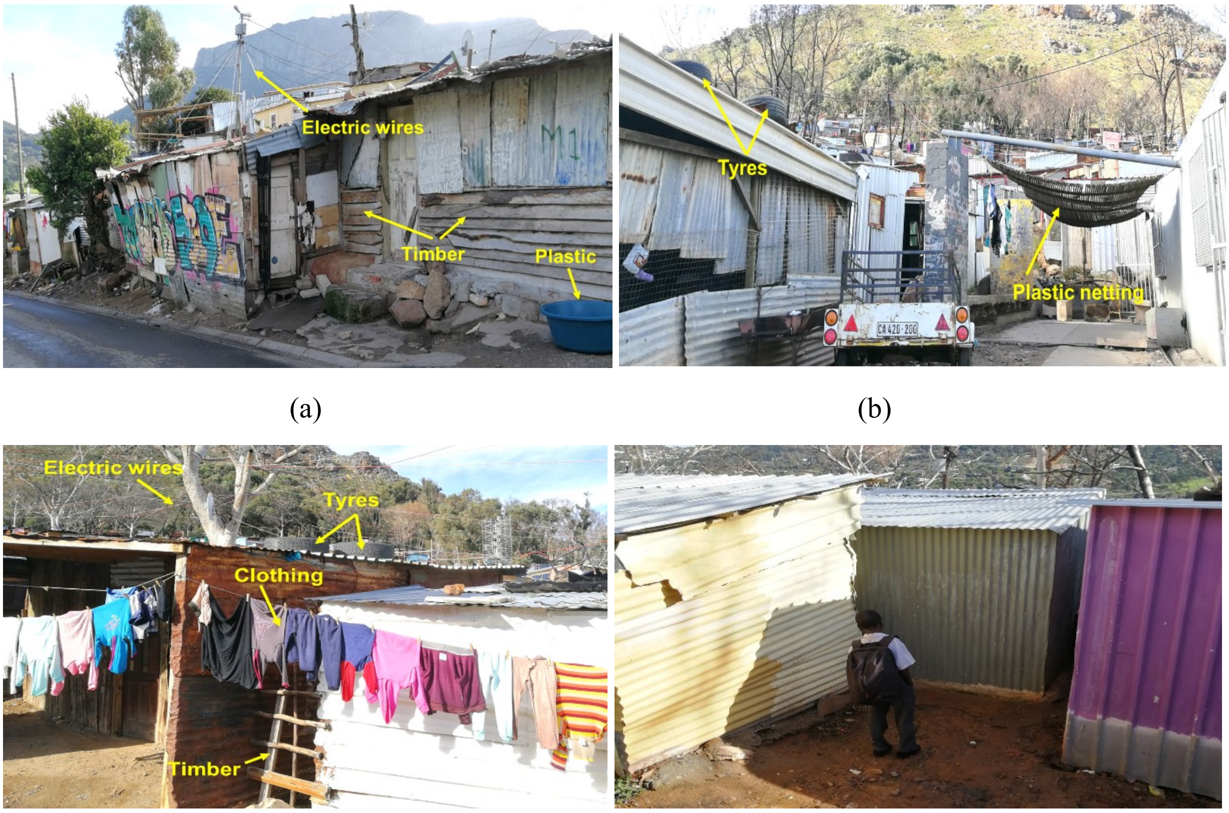
Previous literature data cannot be directly used since it does not match the real situation in South Africa or other Global South countries, resulting in large errors for the analytical results. This paper, therefore, presents a systematic database of the burning characteristics of typical materials found in South African informal settlements. To get consistent experimental results, a cone calorimeter is used to obtain the important burning parameters, including the critical heat flux, ignition time, burning time, maximum heat release rate, and average and maximum flame heights. This work complements other work by the authors where we have conducted quarter-scale compartment experiments [20], full-scale experiments (ISO 9705) [21] and 12/20 full-scale dwelling experiments. This data is fundamental for any future numerical modelling studies and plays an important role in current fire spread analyses within informal settlements. Thirty-two different materials collected from an informal settlement are tested, and more specific results can be found in the following sections.

2. Materials selection and experimental design

Ignition through radiation is important for both the compartment fire development and fire spread between dwellings [22, 23], thus the cone calorimeter, in which the convective contribution is immeasurably small in the horizontal specimen orientation [24], is used to determine the burning characteristics of 32 different materials, collected from a single informal settlement in the Western Cape in South Africa. It should be noted that measuring the HRR in full scale experiments is the simplest and relatively accurate way for the hazard estimation, however informal settlement dimension and fuel load diverse significantly, it is very difficult to test an informal dwelling in a full-scale experiment as a representative work. Thus, bench-scale tests for understanding combustible elements are essential. More information between the benchmark and full scale experiments can be found in [25].

2.1 The determination of the material list

An ad-hoc survey of combustible materials in informal settlement was performed in May 2018 during a guided visit to Imizamo Yethu informal settlement in Cape Town, South Africa, as shown in Figure 1. The dwellings are built very close to one another and a large number of combustible materials distributed within and between the shacks. It can be seen from the Figure 1 (a)-(c) that the timber, plastic, netting, clothing and tyres were placed on the walls and/or roofs of the structures, and sometimes in the space between dwellings. The distances between dwellings are very small, as shown in Figure 1 (d). In addition, it was found that inside the dwellings, multiple layers of vinyl floor covering may be used, while wood is primarily employed for doors and window framing. Walls may be lined with cardboard, timber or other materials.



(a) (b) (c) (d)

Figure 1: Pictures taken in the survey in Imizamo Yethu informal settlement, South Africa showing the many materials that comprise the structural systems and that are used between and on the dwellings, specifically: a) roadside dwellings with a mix of timber and metal wall systems; b) homes with tyres on the roofs and shade netting in between homes; c) timber and clothing spanning between dwellings; and d) the close proximity of dwellings in Imizamo Yethu

Based on the settlement visits and experience of colleagues in South Africa, more than 30 different kinds of materials were identified as potentially combustible and of interest to be experimentally examined. The selection of these materials were conducted in the informal settlements and the valuable feedback the authors received from the firefighters interviewed from the Cape Town Fire and Rescue Services. A literature review was used to check which materials are not currently available and thus need to be tested. Although the list is not exhaustive, these materials are representative of those found in a typical informal settlement dwelling and largely perceived to contribute to the fuel load in the informal settlement conflagrations. This list was filtered for feasibility to that shown in Table 1. Some materials known to be within these homes, such as candles, vegetation, photovoltaic panels, coal, paraffin, electricity cables, and TVs, have not been assessed as there would be no significant difference from literature (i.e. paraffin) or not practical (i.e. vegetation). It should be noted that the material tested reflect the real materials found in informal settlements, which means the thickness and age were uncontrolled, and sometimes unable to be measured. A total of 32 different materials were collected with some materials, such as carpet, cardboard, clothing and newspaper, with multiple different types assessed. For the materials selected, although there is no open literature about them, it can be defined as a combination of different components. For example, carpet: woven acrylic, knitted polyester, mink, cotton, fleece and wool; curtain/trousers/t-shirts: cotton, polyester; women leggings: nylon, spandex, wool or cotton [26-28]. For comparison, the maximum HRR and critical heat flux of these components are listed in Table 2 for reference.

It should be understood that the nature of materials used in informal settlements is highly variable. Construction materials used for homes may vary geographically. People's possessions range in age and quality, sometimes being bought as new items (hence would have similar characteristics to formal homes) whereas other items are obtained second hand and can be very old (meaning that materials could come from decades ago). A relatively new settlement, or one that has been recently destroyed by fire, is likely to have lower fuel loads and newer contents, as opposed to a stable settlement which has been in existence for decades. Nevertheless, this work provides a good benchmark and novel database which can be enhanced with further research and investigations.

Table 1: The material list for the cone calorimeter tests.

No.	Material Type	Specific material	Thickness (mm)	Note
1	Timber	Structure timber	36	Most common, pine
2		Fuel timber	50	Fuel, saligna
3		Masonite timber (MDF)	3	Masonite board, commonly used in furniture, on doors or lining homes
4		Timber furniture 1	16	Chipboard - shelf section

5		Timber furniture 2	16	Chipboard - cupboard section
6	Plastic and rubber	Plastic bag	<1	Woven plastic bag
7		Clear plastic sheet	<1	Used as table cover
8		Shade netting	1	Plastic
9		Tyre	6	Vehicular tyre
10	Cardboard	Cardboard 1	5	Thick cardboard
11		Cardboard 2	3	Thin cardboard
12	Newspapers	Normal paper	<1	--
13		Advertisement	<1	Common leaflet ads in SA
14	Foam	Dark yellow foam	50	Polyurethane foam
15		Light yellow foam	50	Furniture foam
16		Pink foam	19	General packaging foam
17		White polystyrene foam	19	Packaging polystyrene
18		Big green insulation	50	Isotherm insulation, not common
19	Bedding	Colourful blanket	5	Local cheap blanket, very common type
20		Pink blanket	1	Used on bed
21		Pillow cover	<1	--
22	Floor covering	Red welcome carpet	1+3	Welcome mat
23		Green carpet	2+4	Old discarded carpet
24		Yellow carpet	1+5	Typical carpet
25		Vinyl	<1	Polyvinyl chloride
26	Curtain	Shower curtain	<1	100% polyester
27		Yellow smooth window curtain	<1	Thin drape curtain
28		Pink curtain	<1	--
29	Clothing	Blue T-shirt	<1	--
30		Black trousers	<1	Polyester
31		Grey trousers	<1	Cotton
32		Women leggings	<1	--

Table 2: The maximum HRR and critical heat flux from literature for various materials [24, 29-37].

Material Type	Specific material	Peak HRRPUA (kW/m^2)	Critical heat flux (kW/m^2)
Timber	Wood Pulp-propylene	---	8
	Wood (douglasfir)/red oak	119 118	10
	Timber for construction	---	10-14
	Southern pine	134	
Plastic and rubber	Chloroprene rubber	600-1000 (dependent on composition)	20
	Styrene-butadiene rubber		10-15
	Ethylene-propylene rubber		20-23
	Natural rubber		10-17
	Butyl rubber		19
Cardboard	Cardboard	270	8-10

Newspapers	Normal paper	---	10
	Advertisement	---	---
Foam and insulation	Polyurethanes foam	100-128 Foam/cotton fabric combinations in cone	13-40
	Polystyrenes foam		10-15
	Latex foam		16
	Phenolic foam		20
Bedding	Cotton	43	13.7-14.6 Cotton towel
Floor covering	Wool	---	---
	Textile wall covering	---	---
	Vinyl ester	879 977	---
	Ethyl-vinyl acetate	---	12-22
Curtain	Cotton	---	13.7-14.6 Cotton towel
	Acrylic	---	---
	Polyester	169	15 10-15 (PEST) 8-18 (Pure) 13-17 (Polyester-Rayon) 13 (Cellulose- polyester)
Clothing	Wool-nylon	---	15
	Cotton	43	13.7-14.6 Cotton towel
	Polyester	169	15 10-15 (PEST) 8-18 (Pure) 13-17 (Polyester-Rayon) 13 (Cellulose- polyester)
	Nylon	---	13-16
Others	Electrical Cable	--	13-25 PVC/PVC 15 PE/PVC 19 Silicone/PVC
	PV panel	402 (45 kW/m^2)	26
	Candle/paraffin wax	800-4150 (10-40 kW/m^2)	<10

2.2 Experimental design

Cone calorimeter experiments were used to measure the parameters as per ISO 5660 [38]. The materials were cut into the dimension of 100 mm×100 mm, and the maximum thickness of each material was 50 mm [24, 39]. Twenty specimens of each material were prepared. Each material was heated for both ignition and burning rate tests. Before each test, the exhaust flow, gas analysers, cone heater height, load cell and heat flux were calibrated. The lab temperature and relative humidity were respectively 20 °C and 45%.

Two series of experiments were designed: 1. Piloted ignition experiments to determine the critical heat flux (CHF); and 2. Burning rate experiments to understand the materials' response under different high heat fluxes.

For the piloted ignition experiments the initial heat flux the samples were exposed to was 30.0 kW/m^2. Critical heat flux for ignition was determined by the range from the minimum heating intensity that ignited the sample to the maximum heating intensity that did not ignite the sample.

For the burning rate experiments, the time to ignition, burning time, flame height and HRR were obtained for each material. Data was gathered using external heat of 30, 50, 75 kW/m^2, and two tests were repeated for each material at each heat flux.

As shown in Figure 2, the specimen was wrapped in aluminium foil and placed in the standard metal holder for the cone calorimeter experiments. The ceramic fibre blanket was put under the specimen to serve as insulation. It should be noted that, due to the very different properties, the definition of ignition was unified for all the tests: the specimen was considered as ignited after sustained flaming for 4 s in each test [40]. The smouldering, glowing or flash was not considered as ignition, as the visible flame and its radiation are considered more important to fire spread mechanisms in an informal settlement.

Figure 2: Examples of each of prepared specimens for the 32 materials listed in Table 1 before testing.

3. Experimental results and discussion

All the burning characteristics assessed in this study will play a role, to a greater or lesser degree, in both the fire development within the dwelling and the potential fire spread between dwellings. The critical heat flux and average time to ignition of the materials are key components to the development of a fire within a dwelling as well as the potential risk of the fire spreading to another dwelling; lower values of both will increase the speed and risk fire development and fire spread. The burning time is a key parameter in terms of fire spread as the longer a dwelling burns, the longer an adjacent dwellings materials might be exposed to heat fluxes that are critical. The maximum heat release rate of a material is important for the overall understanding of the internal fire development, whilst the average flame height and maximum flame heights are important to understand in the context of fire spread from direct flame impingement.

3.1 Critical heat flux

In each test, the material was initially heated under a 30 kW/m^2 heat flux. Almost all the materials were able to be ignited below the initial 30 kW/m^2, except for specimen materials 16 and 18. For both of these materials, they pyrolyzed very quickly under 30 kW/m^2, but no visible flame was observed. It should be noted that, for specimen material Nos. 16 and 18, once heated, the material rapidly shrunk away from the heating source to the bottom of the aluminium foil, thus increasing the distance between heater and specimen and reducing the heat flux, making it difficult to ignite. It is anticipated that this phenomenon also happens during the real fire, thus although the materials may have big area/volume but would not contribute significantly to the fire development.

The critical heat fluxes of all the materials are illustrated in Figure 3 and heat flux values tested are shown in Table 3 in bold. The accuracy of the values is ±1-2 kW/m^2. It can be seen that the materials 6, 13, 17, 18, 20, 21, 26, 27, 28 and 32 (namely woven plastic bag, newspaper, polystyrene foam, green insulation material, pink blanket, pillow cover, shower curtain, window curtain, pink curtain and women leggings) have relatively high critical heat fluxes of more than 20 kW/m^2 for ignition. Other materials, 8, 9, 14, 15, 19, 23 and 24 (namely plastic shade netting, tyre, Polyurethane (PU) foam, colourful blanket, green carpet and yellow carpet) can be ignited at relatively low heat fluxes under 10 kW/m^2. In particular, the PU foam (No. 14), commonly found in mattresses in informal settlement, has the lowest critical heat flux of 6-7 kW/m^2.

Overall, the curtains (material number 26, 27 and 28), which were expected to be dangerous, were found relatively difficult to ignite with critical heat flux more than 22 kW/m^2. Similarly, newspaper and cardboard, which are commonly used to prevent drafts within informal settlements, were not easily ignited in this experimental set-up. For the newspaper, under lower heat flux, it may smoulder rather than burn with flame, so it was not treated as ignition in this experiment considering the ignition definition in Section 2.2 and its limited effect on the fire spread. However, the PU foam (material number 14 and 15, 6-7 kW/m^2), carpet (material number 23 and 24, 7-8 kW/m^2) and tyres (material number 9, 7-8 kW/m^2, sometimes used as weights on roofs) show great potential ignition risk when subject to low incident radiation. Easily ignitable materials (such as colourful blanket, number 19, 8-9 kW/m^2) are not widely applied in formal homes due to their fire risk, however, anecdotally, they are relatively common in the informal settlements around Cape Town. All the above materials with low critical heat flux should be noted when analysing the fire spread between shacks.

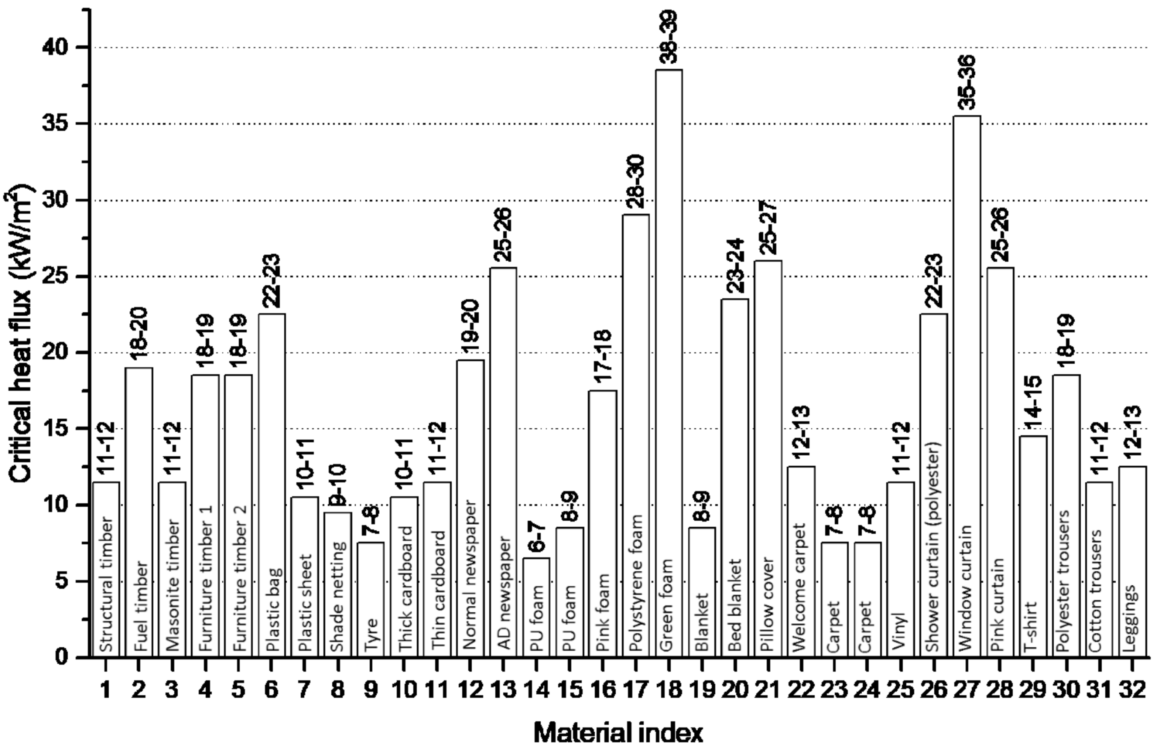


Figure 3: Critical heat flux of the 32 materials listed in Table 1 collected from Worcester

3.2 Time to ignition

To understand more about the potential fire ignition risk, the relationship of incident heat flux and ignition time for the different materials are shown in Figure 4. The curves are separated by the material type categories listed in Table 1. For all the materials tested, three common heat fluxes were used for direct comparisons, specifically the values at 30, 50 and 75 kW/m^2 with each experiment being conducted twice to produce an average time to ignition. It can be seen that within each category, regardless of material thickness, the curves show a similar response with the time to ignition. Only the tyre in Figure 4(b) and green insulation in Figure 4(e) are different from the other material in their respective category. For the tyre, the difference could be caused by the composition and thickness. For 6, 7 and 8, the materials are primarily polyethylene (LDPE, LLDPE, etc.), while the tyre is made of synthetic rubber and thicker (6 mm) than other materials (≤ 1 mm). For green insulation, its ability to shrink under heat flux is considered to play a key role for the difference observed.

The specific ignition times under different heat fluxes are summarized in Table 3. Bold type means ignition time at critical heat flux. It can be seen that when subject to the critical heat flux, the material Nos. 29, 31 and 32, which are all clothing type, show shortest ignition time of smaller than 20 s under low heat flux (below 15 kW/m^2), which may accelerate the fire spread significantly. In informal settlement, clothing may not only exist inside a room and within cabinets, but also could be hanging between dwellings, as shown in Figure 1(c), which can exacerbate fire spread. Among all the materials, timber type material needs longest time for ignition despite low critical heat fluxes. However, when the heat flux increased to more than 50 kW/m^2 which occurred in fully developed fire [41], all materials will be ignited within 40 s (See Table 3), with most in less than 10 s (No 18 is excluded due to it shrinking during the experiments), which is potentially highly dangerous.

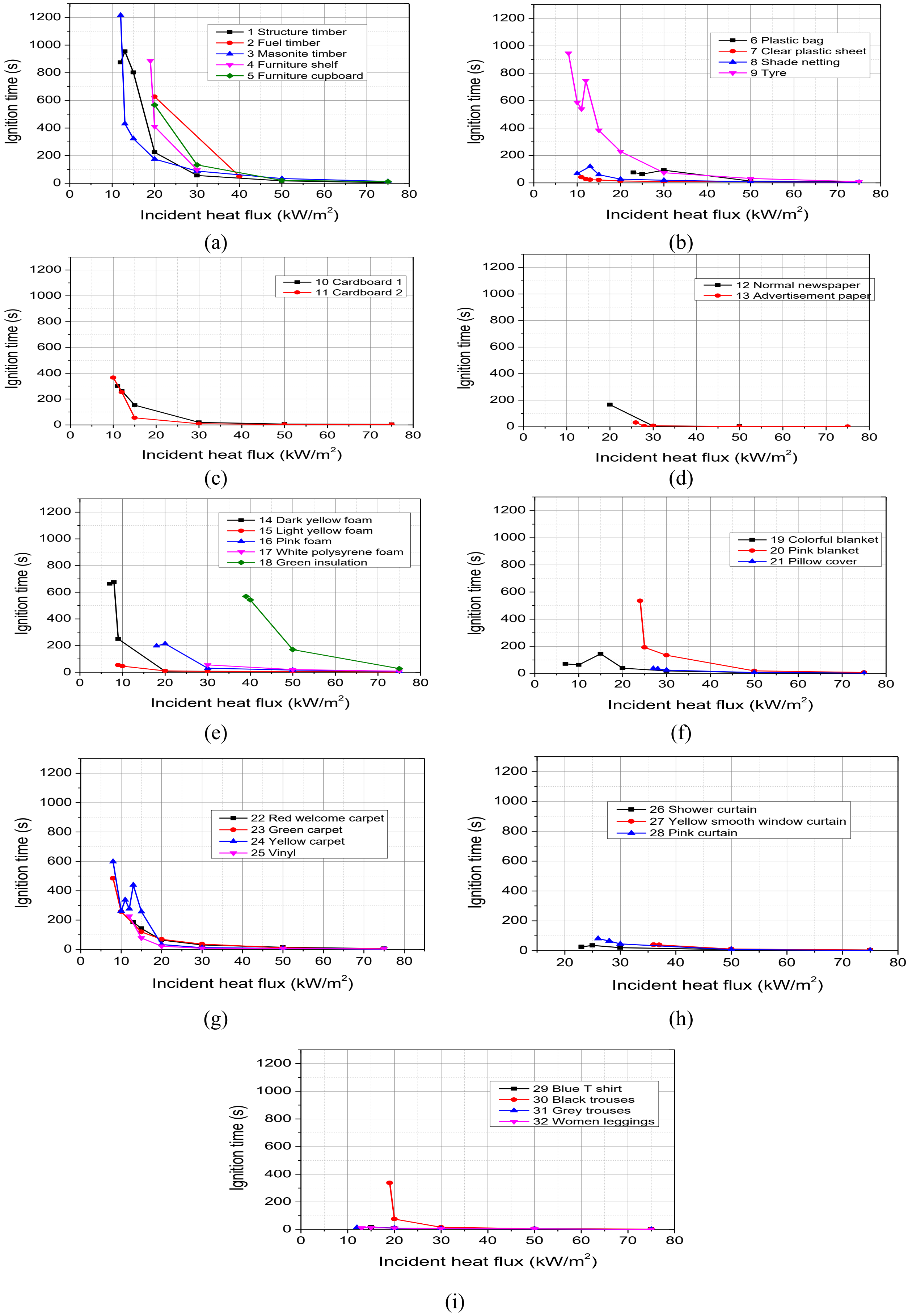


Figure 4: The relationship between time to ignition and incident heat flux.

Table 3: The summary of average ignition time under different heat fluxes for the materials listed in Table 1.

	Heat Flux (kW/m^2)																													
Material No	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**17**	**18**	**19**	**20**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**30**	**35**	**36**	**37**	**38**	**39**	**40**	**50**	**75**
1						no	no	**875**	954		768				224								57							18	5
2											no		no		**627**														51		
3						no	no	**1216**	431		323				175								89							34	14
4											no		no	**886**	411								97								
5											no		no		**567**								133							21	13
6															no	no	**76**		64				93							13	7
7						no	**42**	28	23		21				14								10							9	3
8				no	no	**68**			120		60				27								19							9	5
9		no	no	**946**		588	539	746			384				229								74							32	9
10						no	**301**	264			153												20							7	5
11						no	no	**253**			55												9							4	3
12						no					no		no	no	**166**								6							4	1
13															no				no	**31**		4	7							1	1
14		no	**663**	675	249										7								8							7	2
15	no			no	**54**	46									10								7							4	1
16											no	no	**198**		214								30							16	7
17															no				no			no	**138**							20	8
18																							no	no			no	**569**	543	170	27
19	no			no	**71**	64					145				40								19							7	4
20															no		no	**535**	193				135							20	8
21															no				no		**38**	35	25							8	3
22						no		no	**186**		143				64								31							15	6
23	no		no	**485**		258					120				69								37							11	5
24		no	no	**598**		263	338	277	439		258				33								12							8	2
25						no	no	**227**			53				22								8							6	4
26															no	no	**25**		35				20							7	4
27																							no	no	**40**	39				11	5
28															no				no	**81**		65	45							7	2
29								no		no	**18**				10								8							5	2
30											no	no	no	**338**	76								17							7	3
31						no	no	**15**			58				11								7							5	2
32						no		no	**12**		13				11								7							5	1

Notes: “no” means no ignition occurred during the test of 1200 s; **Bold type** means ignition time at critical heat flux

3.3 Burning characteristics under different heat fluxes

The external heat flux to generate continuous burning for materials is different when the fire is growing to when it is fully developed, with heat fluxes in the ranges of 20-60 kW/m^2, and >50 kW/m^2, respectively [42]. The choice of which heat flux to assess a material under is normally governed by several different conditions. For informal settlement fires, previous research has shown that the fuel load is around an average of 410MJ/m^2, however, this can be as high as 1000-2000MJ/m^2 depending on whether fuels are being stored in and around the homes [43]. Therefore, it is necessary to understand the burning behaviour of the materials under several different heat flux conditions. The three heat fluxes of 30, 50, and 75 kW/m^2, were thus selected to represent the variety of fluxes possible due to the composition and magnitude of the fuel loads found in informal settlements.

Each material was tested six times (twice under each heat flux) and their burning characteristics averaged over those six experiments. The average burning characteristics of the ignition time, burning time and maximum HRR, are shown in Figure 5-7, with the error bars representing the maximum and minimum values recorded for that material. Flame length is presented in the next section. The maximum HRR or maximum flame height represents the biggest value in each test, and these maximums are averaged across 6 tests; while the average flame height is the mean value in each test from ignition to flame out, and then averaged across the 6 tests of each material. It should be noted that materials number 2 and 4 were not included in the burning rate tests due to the lack of material resource, however, we assume that material No. 4 has similar burning characteristic of No. 5 as both materials were sampled from different parts of the same piece of furniture.

The average time to ignition from 6 burning rate tests (30, 50, 75 kW/m^2) for each material is shown in Figure 5. It can be seen from the figure that the materials No. 11-15, 29, 31 and 32, namely cardboard, newspaper, PU foam and some clothing, have the smallest ignition time (< 5 s). This result is reasonable as these materials are usually very thin and are relatively flammable materials. Meanwhile, the No. 5, 17, 18 and 20, namely furniture, polystyrene foam, green insulation, bedding pink blanket, have much larger values (> 50 s). The error bars are relatively large for these materials. Different to other parameters, the ignition time is very sensitive to the incident heat flux. From the average value, some materials took a long time for ignition to occur, however, when subject to 75 kW/m^2, the pyrolysis would be significantly accelerated, resulting in a large difference between minimum and maximum values. The difficulty of ignition for No. 17 and 18 may be caused by the material melting to the bottom of specimen holder, decreasing the height of specimen. It should be noted that some material has low critical heat flux but needs a relatively long time to ignite, i.e. tyre, while some have high critical heat fluxes but may be ignited very shortly, like newspaper and women leggings. Thus, these two parameters do not show a strong relationship from the experimental results.

Figure 6 shows the average burning time for each of the materials tested; and shows materials No. 1, 5, 9, 14 and 24, namely structural timber, furniture timber, tyres, PU foam and yellow carpet, have long burning times (> 200 s). Note that for No. 1 and 5, in each test the burning time was larger than 1200 s. As the test was ceased at 1200 s, so the recorded burning time of 1200 s is smaller than the true value. Meanwhile, No. 7, 11-13, 21, 27, 28, 30 and 32, namely clear plastic, cardboard, newspaper, pillow cover and clothing, have relatively short burning time (< 30 s) due to their small thickness (normally < 1 mm) and so were almost completely consumed during the experiment.

Two methods, proposed by Janssens [44] and Brohez [45], respectively, were used to calculate the HRR. As the results are similar, only the maximum HRR results from Janssens' method with the measurement of O_2, CO_2 and CO, are presented in Figure 7. Figure 7 shows that materials No. 3, 9, 14, 15, 23 and 24, namely Masonite board, tyre, PU foams and carpet, have the largest HRR (> 300 kW/m^2). However, the material, No. 12, 13, 20, 21 and 26-28, namely newspaper, bedding and curtains, have very low HRR (< 50 kW/m^2), and therefore are unlikely to contribute a lot to the fire development within the home of origin.

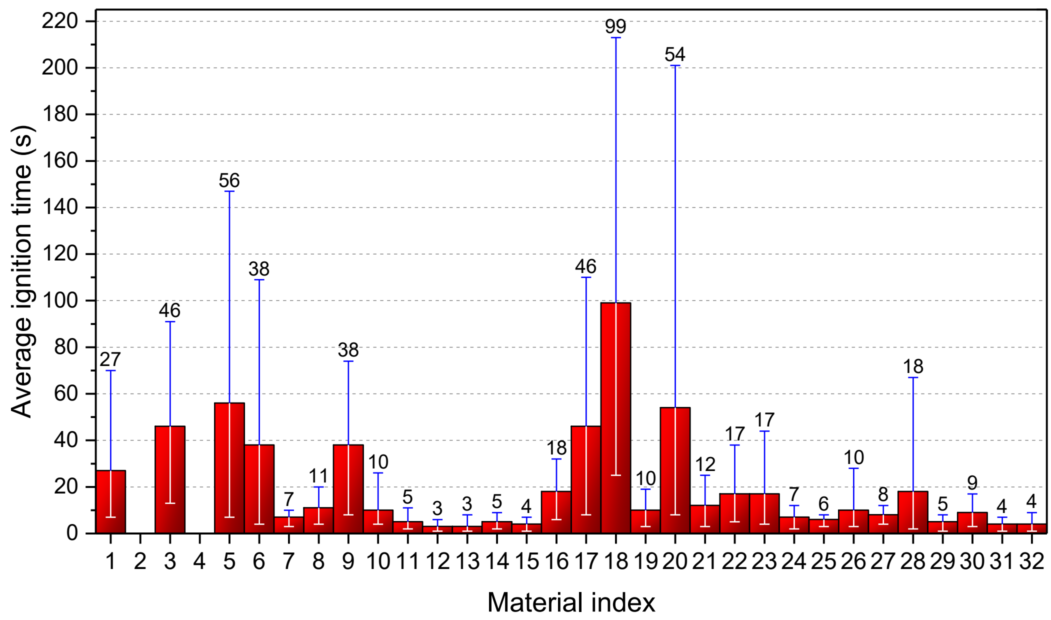


Figure 5: The average ignition time of materials (numbers relating to average time to ignition for each material number) with associated maximum and minimum error bars.

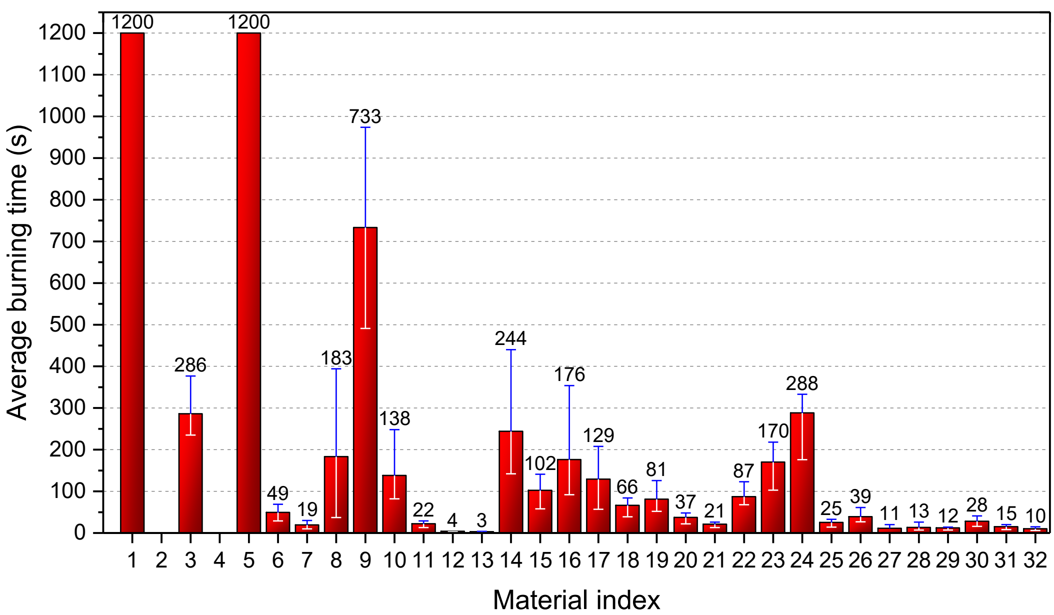


Figure 6: The average burning time of materials (numbers relating to average burning time for each material number) with associated maximum and minimum error bars.

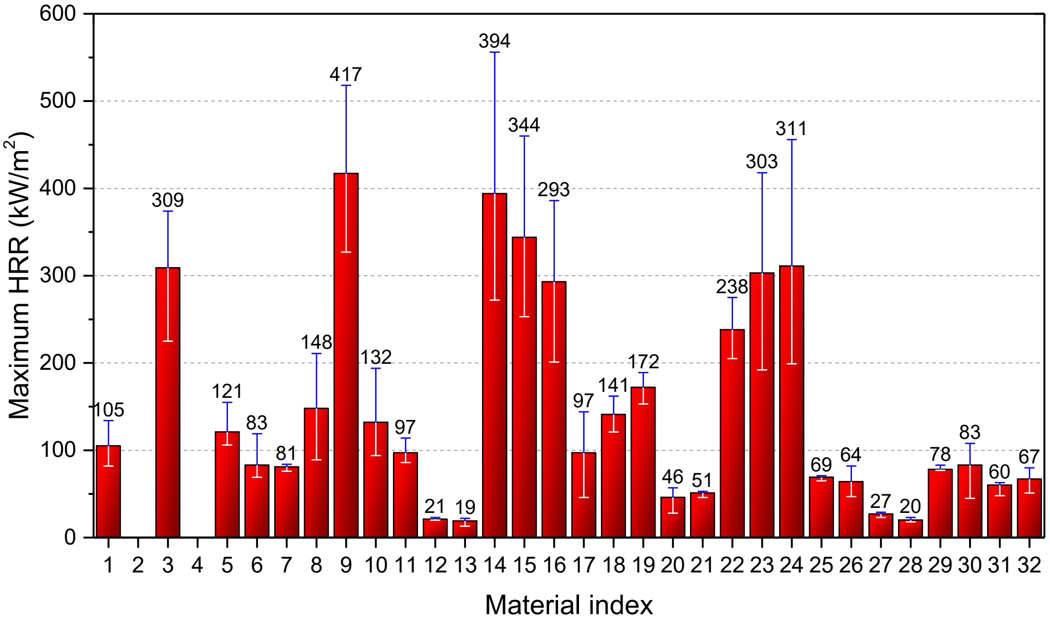


Figure 7: The average maximum HRR of materials (numbers relating to average maximum HRR to ignition for each material number) with associated maximum and minimum error bars.

Other serious phenomena observed in these experiments were ejection of burning embers and smouldering of the materials. During the burning of the tyre sample, a large amount of flaming debris splashed and fell on the platform, while the glowing of Masonite timber continued after the flames had died out. In informal settlements, tyres are often used to weigh down the roofs in case of wind and Masonite timber is often used as internal wall finishing, thus, these fire phenomena are potentially dangerous to informal settlements.

Moreover, the specific values of maximum HRR and burning time at different heat fluxes are presented in Table 4. It can be seen from this table that the maximum HRR normally increases with increases to the incident heat flux, and this phenomenon is more significant for wood, carpet and PU foam. However, as the incident heat flux increases, the burning time decreases, except for wood which always reached 1200 s of burning time. These trends are also significant for PU foam (No. 14) and carpets (No. 23 and 24). For these thick materials, their fire behavior should be considered heat flux dependent. It can also be found that for some other materials which are thermally thin materials under these heat fluxes, such as the newspaper, clothing and bedding, the variance of maximum HRR and burning time at different heat fluxes is limited as they can burn completely in a very short time.

Table 4: Average of the maximum HRR and burning time at different heat fluxes (two experiments per heat flux)

	30 kW/m^2		50 kW/m^2		75 kW/m^2	
Material No	HRR (kW/m^2)	Burning time (s)	HRR (kW/m^2)	Burning time (s)	HRR (kW/m^2)	Burning time (s)
1	81	1200	99	1200	134	1200
2	--	--	--	--	--	--
3	225	315	327	280	374	266
4	--	--	--	--	--	--
5	102	1200	107	1200	155	1200
6	61	65	69	49	119	32
7	76	21	82	13	84	22
8	89	81	145	263	211	205
9	327	974	406	--	518	491
10	94	153	106	176	194	84
11	86	28	92	24	114	15
12	20	4	20	4	23	3
13	13	4	22	3	22	2
14	272	341	352	218	556	172
15	253	137	317	93	460	76
16	201	296	294	123	386	110
17	46	208	101	103	144	77
18	--	--	143	49	142	82
19	159	72	177	52	181	119
20	47	38	35	75	55	27
21	46	24	52	24	53	16
22	205	80	235	86	274	95
23	192	199	300	195	418	118
24	199	334	279	279	456	252
25	65	33	72	21	71	19
26	47	57	62	28	82	32
27	--	--	25	18	29	15
28	18	21	19	9	23	10
29	77	14	74	11	83	11
30	45	38	94	24	108	23
31	61	20	56	15	61	9
32	63	12	59	8	80	10

4. Discussion

In this work, the primary parameters of these combustible materials, including critical ignition heat flux, ignition time, burning time, maximum HRR, maximum and average flame heights are obtained, as listed in Table 5. Note that flame length is not a standard reporting variable for Cone Calorimeter data, but to provide more information, it is given and the threshold was set as 0.7 for recognition of flames. To give a reference, the maximum HRR calculated by the way of Brohez et al. [45] is presented as well.

By comparing the results to Table 2, it was found that the burning behaviour varies dramatically based on the components of each item. For example, the critical heat flux for curtains consisting of different polyesters could vary from 8 to 18 kW/m^2, while the curtains tested in this study vary from 22 to 36 kW/m^2, which means that the values in this study are all larger than that in the literature. In addition, for the rubber, the critical heat flux in the literature varies from 10 to 23 kW/m^2 which is all larger than the tyre of 7-8 kW/m^2 in this work. For other materials like the vinyl floor covering, the critical heat flux in this study (11-12 kW/m^2) is smaller than the range of what is found in the literature (≈12 to 22 kW/m^2). However, for natural products, like wood, the values in this study of the critical heat flux (≈11-20 kW/m^2) are similar to the range of what is found in the literature (8-14 kW/m^2). One of the critical materials for the fire development within the compartment (e.g. time to flashover) is the wall lining materials. As the cardboard was found to be one of the most used lining materials (along with materials such as timber boards and various insulation materials), it is essential to understand how much heat the cardboard would release when it burns. In previous work found in the literature, the peak HRR was found to be around 270 kW/m^2; around 40 % more the maximum peak Heat Release Rate found in this study. This finding highlights the importance of this study, where it is essential to create a database for the burning behaviour of the materials to better understand how fires develop and spread. This will eventually enhance the accuracy of the risk mapping exercises [46]. Relying on literature is always an option, however, it may dramatically increase the error of any engineering-based prediction if data is too generic. In particular, in computer modelling, the use of literature compared to context-specific burning characteristics values could highly affect our ultimate understandings of the fire dynamics within the informal dwellings and could produce erroneous conclusions.

To provide an initial risk index, the values in Table 5 are highlighted: the green are considered relatively safe values among all materials; meanwhile, the red are the dangerous values. The criteria for classifying heat flux is made according to the absolute value in a compartment fire [41]: if critical heat flux is larger than 20 kW/m^2, it will be highlighted green (can only be ignited after flashover); if < 10 kW/m^2, then red. For the other parameters, no specific criteria can be found in literature, so by comparing the data, the values which are significantly larger or smaller are selected as criteria: ignition time at critical heat flux: > 550 s green, < 50 s red; average ignition time from burning rate tests (30-75 kW/m^2): red > 45 s green, < 10 s red; burning time: < 30 s green, > 200 s red; maximum HRR: < 60 kW/m^2 green, > 300 kW/m^2 red (Janssens method [44] used for reference); average flame height: < 90 mm green, > 170 mm red; maximum flame height: < 200 mm green, > 290 mm red. The values are selected based on the overall data distribution and the highlighted number is mostly controlled under 30% of total sample numbers.

It can be established that some materials have high fire risk in relation almost all parameters tested, such as tyre (No. 9), PU foam (No. 14 and 15), and carpet (No. 23 and 24). In particular, for PU foams, which are commonly used for mattresses in informal settlement [43], are potentially very dangerous materials with all parameters highlighted red. On the other hand, without considering the fabric and areas in real dwelling in informal settlement, the newspapers (No. 12 and 13), bedding (No. 20 and 21) and curtains (No. 27 and 28) appear not to contribute significantly to the fire intensity. However, it should be noted that these materials, as well as clothing, would be ignited in a very short time if the critical heat flux is reached and the surface flame spread rate may be large, resulting in quick fire spread at the very early stage. For other materials, their parameters show inconsistency which cannot be directly assessed.

Table 5: Summary of important burning characteristics of the materials collected from the Worcester Informal Settlement

No.	Materials	Critical HF (kW/m^2)	Ignition time (s)		Burning time (s)	Maximum HRR Janssens (kW/m^2)	Maximum HRR Brohez et al. (kW/m^2)	Avg flame height (mm)	Max flame height(mm)
			Ignition time at CHF	Average above 30 kW/m^2					
1	Structure timber	11-12	875	27	1200	105	120	116	213
2	Fuel timber	18-20	627					--	--
3	Masonite timber	11-12	1216	46	286	309	389	124	270
4	Timber furniture 1	18-19	886					--	--
5	Timber furniture 2	18-19	567	56	1200	121	154	88	272
6	Plastic bag	22-23	76	38	49	83	57	110	267
7	Clear plastic sheet	10-11	42	7	19	81	56	119	239
8	Shade netting	9-10	68	11	183	148	110	144	280
9	Tyre	7-8	946	38	733	417	370	201	306
10	Cardboard 1	10-11	301	10	138	132	157	153	313
11	Cardboard 2	11-12	253	5	22	97	108	174	252
12	Normal paper	19-20	166	3	4	21	19	145	295
13	Advertisement	25-26	31	3	3	19	16	118	236
14	Dark yellow foam	6-7	663	5	244	394	400	222	315
15	Light yellow foam	8-9	54	4	102	344	344	194	292
16	Pink foam	17-18	198	18	176	293	239	122	274
17	White polystyrene foam	28-30	138	46	129	97	86	68	211
18	Big green insulation	38-39	569	99	66	141	126	111	247
19	Colourful blanket	8-9	71	10	81	172	179	119	279
20	Pink blanket	23-24	535	54	37	46	47	51	186
21	Pillow cover	25-27	38	12	21	51	52	148	254
22	Red welcome carpet	12-13	186	17	87	238	273	172	284
23	Green carpet	7-8	485	17	170	303	293	161	323
24	Yellow carpet	7-8	598	7	288	311	278	177	285
25	Vinyl	11-12	227	6	25	69	59	77	180
26	Shower curtain	22-23	25	10	39	64	41	132	231
27	Yellow smooth window curtain	35-36	40	8	11	27	19	155	190
28	Pink curtain	25-26	81	18	13	20	18	123	218
29	Blue T-shirt	14-15	18	5	12	78	83	159	286
30	Black trousers	18-19	338	9	28	83	88	190	288
31	Grey trousers	11-12	15	4	15	60	55	161	310
32	Women leggings	12-13	12	4	10	67	63	177	317

Furthermore, as the different parameters will play different roles at different fire stages, it is important to assess these combustible materials from different aspects:

1) Fire development inside the dwelling, determined by critical heat flux and ignition time

Before fire spreads from one dwelling to another, understanding fire development within the compartments is vital. A value of 20 kW/m^2 is normally treated as flashover definition at the floor level [19], which means around 70% of these materials (highlighted in red and not-highlighted material in critical heat flux column in Table 5) are ignited before flashover according to the critical heat fluxes. In particular, the PU foam and carpets have the lowest critical heat flux and are anticipated to ignite very easily. In addition, the clothing could be ignited very quickly within half minute. After the flashover has occurred, with heat fluxes above 50 kW/m^2, almost all the materials would be ignited within 20 s from Table 5. All the curtains, bedding and newspapers tested can be ignited very quickly as well but can only be ignited when or just before flashover occurs according to above assumption. It should be noted that the results are based on purely radiative heating without brand and flame. The compartment fire development difference between the formal and informal settlement is significant due to the nature leakage, opening condition, wall condition and fuel load, which may not be reflected from the burning of combustible materials.

2) Fire spread between dwellings, determined by critical heat flux, ignition time, burning time and flame height

After flashover occurs, the compartment fire becomes ventilation controlled, thus the fuel load and fabric of room would not affect the fire development significantly. However, with a developed fire scenario, the ejected flame emerges from the windows and the door, which would initiate the fire spread between dwellings. The shade netting (No. 8) and the hanging clothing (No. 29-32) outside the dwelling can be ignited easily and quickly. In particular, the hanging clothing (No. 30-32), with largest flame heights (highlighted red in Table 5), will enhance the flame spread. The tyre (No. 9), with low critical heat fluxes (highlighted red), often placed on roofs or seen hanging between dwellings, as shown in Figure 1, may need as long as 15 minutes to ignite under radiation of 7-8 kW/m^2, but once ignition, it will burn heavily. In particular, the tyre with the lowest critical heat flux (only after PU foam) and the longest burning time of 733 s (only after wood) and burning brands will cause much more potential risk for fire spread. Moreover, with the short distance between dwellings and the presence of combustible construction materials such as timber wall, adjacent dwellings would potentially be ignited when subject to more than 30 kW/m^2.

3) Fire severity, determined by burning time and maximum HRR

The fire severity includes both the fire development inside the dwelling and the fire spread between them, which may be affected by the wind condition, home distribution and amount and characteristics of the combustible materials. From the parameters measured in this work, the burning time and HRR, which relates to the effective heat of combustion [19], are discussed for the fire severity. Inside the dwelling, ignited in early stage of fire, Masonite timber (No. 3) and PU foam (No. 14 and 15) with a highest burning time and maximum HRR will contribute most to heat the whole compartment, thereby accelerating the occurrence of flashover. Although the carpet has small CHF, it is on the floor so may not be ignited before flashover if the fire occurs, for instance, on the furniture. Outside of the dwelling, the tyre, which is highlighted red in both parameters, needs more attention with regards to the risks and potential mitigation of those risks for fire spread between dwellings.

Considering the most potentially dangerous combustible materials in relation to the three aspects listed above, as an example, the HRR of women leggings, shade netting, tyre, PU foam, carpet and Masonite timber, at different heat fluxes of 30, 50 and 75 kW/m^2, are plotted Figure 8. The curves are significantly different under different heat fluxes and some materials, such as carpet, have two peaks due to its two-layer composition (wool cover and plastic bottom). This information can be implemented in a further numerical model. For reference, the HRR curves of the other materials can be found in the appendix and all the original data are available in [47].

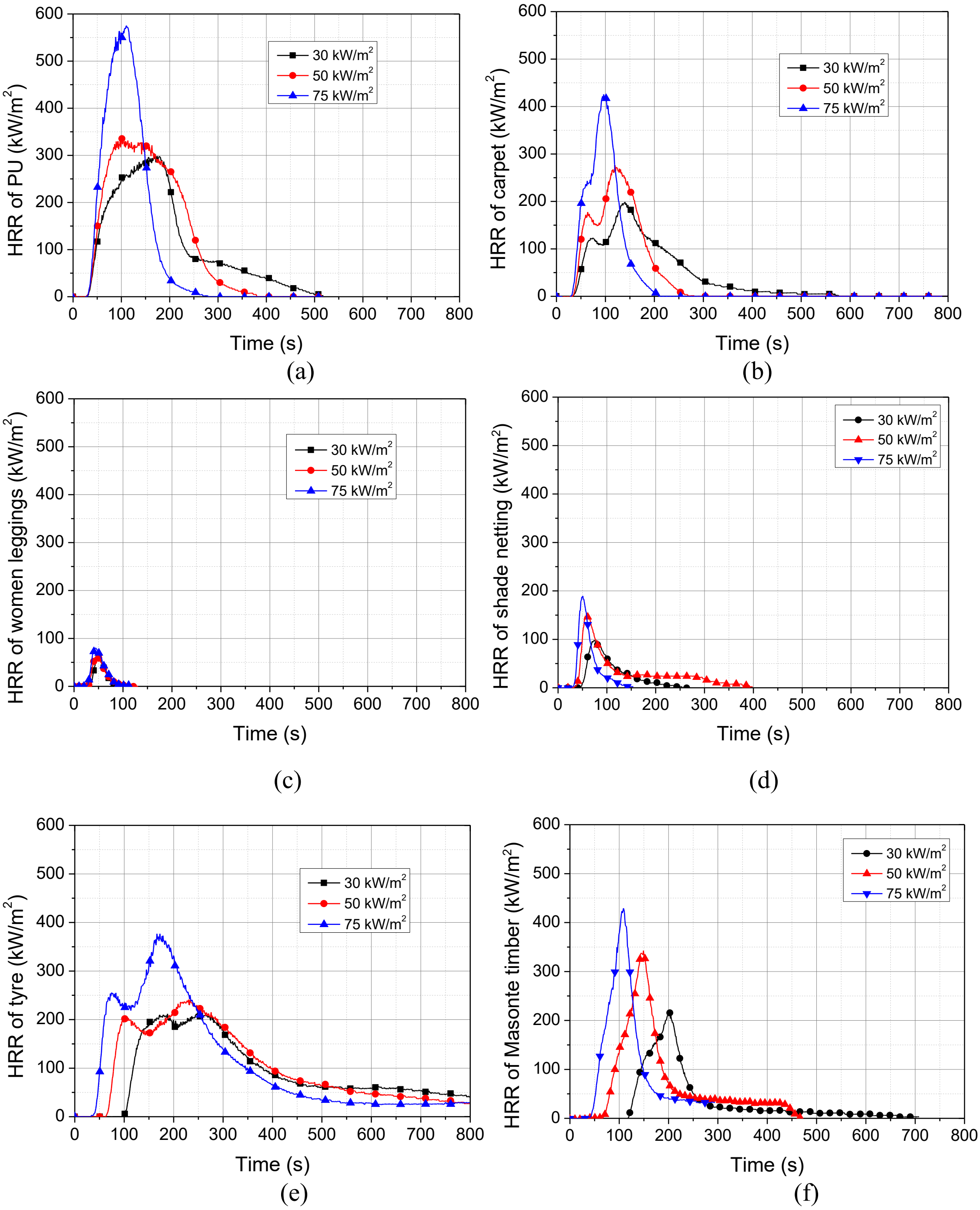


Figure 8: Seleceted HRR-time curves of the materials with largest risk associated with different aspects of: fire development (a)-(c); fire spread (c)-(e); fire severity (a)(b)(e)(f). Specifically a) PU foam, b) carpet, c) leggings, d) shade netting, e) tyre, and f) Masonite timber.

5. Conclusions

In this work, a list of combustible materials from an informal settlement was determined through an ad-hoc site survey and local expertise. A systematic experimental study, including 345 cone calorimeter tests, was then performed to deepen the understanding of the burning behaviour of these materials. The critical heat flux and the burning behaviour under three different heat fluxes (30 kW/m^2, 50 kW/m^2, 75 kW/m^2) were obtained. The important parameters, including the critical ignition heat flux, ignition time, burning time, maximum HRR, and maximum and average flame heights, were determined. Thus, a single database with a consistent level of information of 32 different typical combustible materials collected from informal settlements was established. To understand the risk more accurately, the fire risk in informal settlements should be divided into different aspects: fire development inside the dwelling, fire spread between dwellings and fire severity. The materials contribute in significantly different aspects. The primary conclusions are as follows:

1) A materials survey within an informal settlement indicated a large diversity of combustible materials and distributions: the construction materials, furniture and the roof materials are all highly flammable, which are distributed inside the dwelling, on the roof and hanging between the dwellings.
2) Overall, tyres, PU foam and carpets can be considered the highest risk materials: tyres are risky for dwelling-to-dwelling fire spread; PU foam is risky for initial fire growth; carpet is risky for intensity of fully-developed fires.
3) Newspapers, bedding and curtains appear do not contribute significantly to the fire intensity, however, their flame spread rate can not be ignored which may affect the fire spread. If they cover a large area, it may result in a large initial HRR which significantly reduces the time to flashover, even if they do not contribute a significant proportion of the total fuel load.
4) For the fire development, according to the materials tested in this work, most (70%) of these combustible materials will be ignited before flashover. PU foam, carpets and clothing can be ignited easily and quickly.

5) For fire spread, the hanging clothing and shade netting will be ignited easily. Although the tyre ignition time at critical heat flux is long, it has the second lowest critical heat flux and the second longest burning time and burning brands will cause a much greater potential risk for fire spread.
6) In terms of fire severity, several factors may be important, but in this work, tyre, PU foam, carpets and Masonite timber can be considered the highest risk materials within informal settlements for both fire development and fire spread; however, this risk will depend on the total amount, location and orientation of materials as well.

More quantitative analysis needs to be performed for accurate fire risk assessment of these materials. As the materials in this work were collected from a specific informal settlement in South Africa, more informal settlement materials from different countries can be tested for further comparison. The outcomes of this work in a typical informal settlement will allow for more quantified and representative modelling of informal settlement dwelling fire development, improved risk mapping of informal settlement fire spread, and highlights the need to consider interventions to improve the materiality of informal settlements to reduce fire risk.

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